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BEAM CHOPPER DEVELOPMENT AT LAMPF

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In order to reduce pileup limitations on μSR data rates, a fast chopper for surface muon beams was built and tested at LAMPF. The system allowed one muon at a time to be stopped in a μSR sample in the following way: A surface beam from the LAMPF Stopped Muon Channel was focused through a crossed-field beam separator and onto a chopper slit. With the separator E and B fields adjusted properly, the beam could pass through the slit. The beam to the μSR sample was turned on or off (chopped) rapidly by switching the high voltage applied to the separator plates on or off within approximately 500 ns; with the E field off, the B field deflected the beam, dumping it near the slit. We demonstrated that, with improved electronics, we will be able to stop a single muon in a μSR sample as frequently as once every 20 μs and that data rates for the system can be a factor of five higher than is attainable with unchopped beams. The observed positron contamination of the beam was less than five percent, and the ratio of the muon rate with beam on to the rate with beam off was 1540.

1. INTRODUCTION

This paper summarizes the results of an experimental study of muon beam chopping as a technique for reducing pileup limitations on data rates in time-differential μSR experiments /1/ performed at the Stopped Muon Channel (SMC) at the Clinton P. Anderson Meson Physics Facility (LAMPF). Results of measurements of beam size and muon rate for the unchopped-beam mode are compared with predicted values, and the measured muon rate is used to predict rates for the chopped-beam mode. Results of measurements of beam rise and fall times, beam extinction efficiency, positron contamination, beam asymmetry, data rates, and background are also presented.

2. MUON PILEUP

2.1. Unchopped-beam mode

Data rates in time-differential μSR experiments cannot be increased indefinitely simply by increasing the flux rate of muons on the sample because there are data-rate limitations due to muon pileup in the sample. This is evident from the following considerations. The information of interest in a μSR experiment is the distribution of time intervals between the arrival of a muon in the sample and the subsequent detection of the decay positron with a positron telescope. To avoid ambiguities resulting from the presence of more than one muon in the sample at a time, the data acquisition electronics must require that there be "pileup" intervals, τ_{pu} (usually about twelve microseconds long), free

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of muon stops both before and after arrival of the muon associated with a subsequently detected positron. If this condition is not satisfied, i.e., if there is muon pileup, all muons involved are rejected.

The rate, R_g, of good muons, i.e., those that are not rejected because of pileup, can be used as a measure of the μSR data acquisition rate. It is evident that, as the muon stop rate in the sample increases from zero, the rate of good muons, and therefore the data rate, increases roughly linearly with the incident muon rate until significant numbers of muons are rejected by pileup. At some incident rate, the good muon rate reaches a maximum and then decreases as pileup causes rejection of an increasing fraction of the stopping muons. R_g is expressed by the formula

$$R_g = Re^{-2R\tau_{pu}}$$

where R is the instantaneous rate of muon stops. This is illustrated in Fig. 1 where the good muon rate is plotted vs. muon stop rate for a hypothetical case for which τ_{pu} is 12 μs.

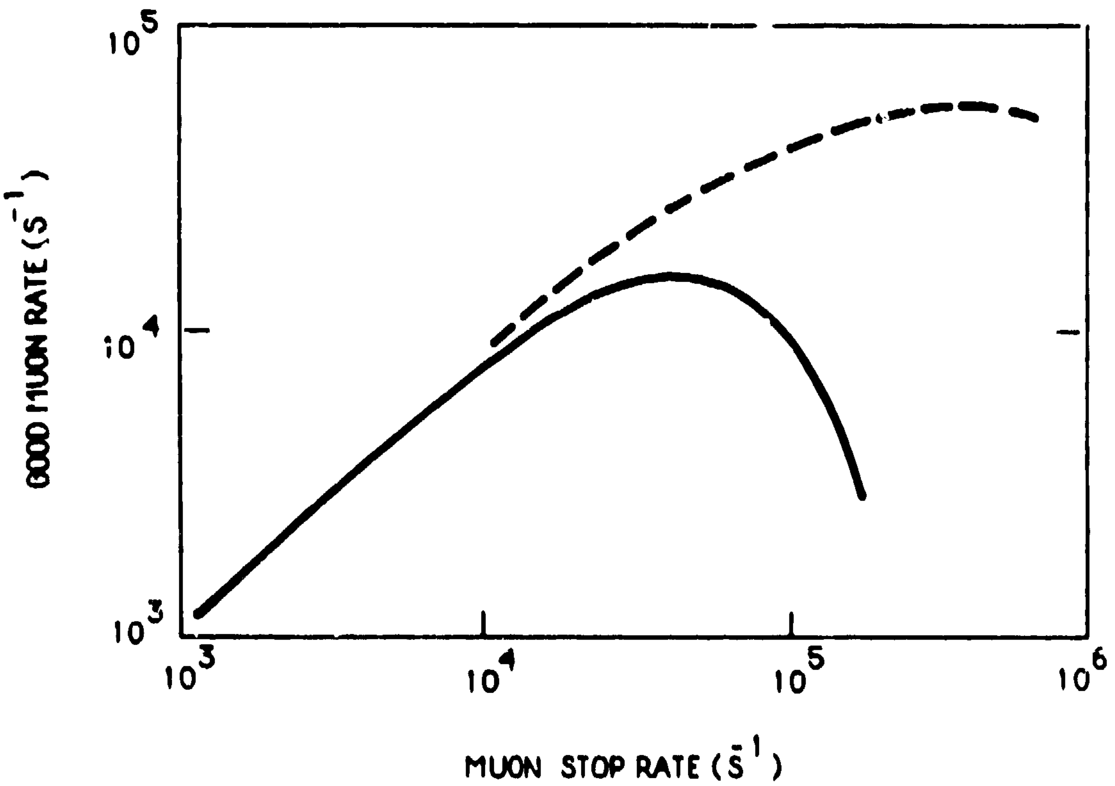

Fig. 1. Illustration of the effect of muon pileup on good muon rates for hypothetical chopped and unchopped beam experiments. Solid curve is for the unchopped beam case, dashed curve is for the chopped beam case. τ_{pu} = 12 μs for both cases and τ_r = 0.5 μs for the chopped beam.

This result has been verified both by computer simulations and by putting pulses from a radioactive source through a pileup module and measuring pileup rates.

2.2. Chopped beam mode

Muon pileup can be reduced, and therefore higher data rates can be attained, by turning the beam off (chopping) quickly to exclude subsequent muons as soon as one triggers the M counter. After a period of time allotted for detection of the decay positron, another muon can be admitted by turning the beam on again.

With this arrangement good muon rates are limited by three factors:

(i) The average waiting time, τ_w (given by $\tau_w = 1/R$) for a muon to trigger the M counter. In this study the time was typically 2 μs. Since this is a small fraction of the total time between events, as discussed in item (ii), it is not a significant limitation.

(ii) The length of time, τ_p, allocated to waiting for the decay positron plus the time required for processing the time-interval information. This total time is typically 15-20 μs and is required for both the chopped and unchopped beam modes of operation.

(iii) Muon pileup. Even in the chopped beam mode, if the instantaneous muon rate is so high that the chopper does not turn the beam off before a second muon arrives, muons will be rejected because of pileup. Pileup is insignificant, however, if the chopper response time, τ_r, is a small fraction of the average time (≈2 μs) between muon arrivals. Neglecting the effect of chopper rise/fall times we find

$$R_g = \frac{Re^{-R\tau_r}}{1 + R(\tau_{pu} + \tau_r)}$$

for the rate of good muon arrivals. This rate is also plotted in Fig. 1, demonstrating the substantial rate enhancement possible with chopping.

3. CHOPPER DESCRIPTION

As Fig. 2 shows, the system studied comprised two main components:

(i) A crossed-field (E and B) separator with a downstream chopper slit and associated high-voltage power supplies and switching circuits /2/, and

(ii) The LAMPF μSR spectrometer consisting of a Helmholtz coil, M counter, and positron telescopes. The spectrometer was configured for a 100-gauss transverse field for this study.

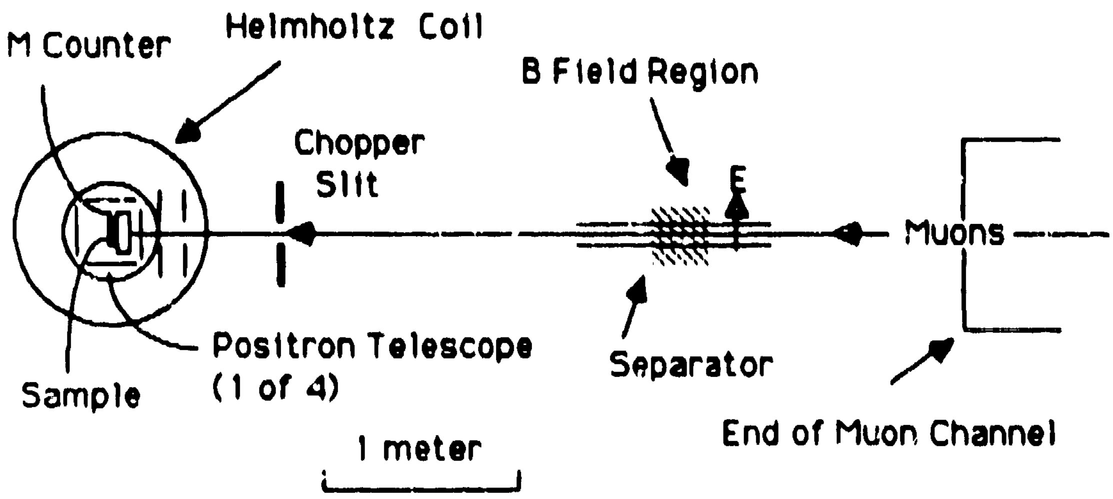

Fig. 2. Side view of chopper setup.

During the chopper studies, the LAMPF proton beam current on the 4-cm-long carbon pion/muon production target was typically 850 μA (520-μs macropulses at 108 Hz). The SMC was tuned to transport 25.9-MeV/c surface muons to the μSR sample, which was a 3-cm-diam, 3-mm-thick copper disk. The muons passed between the high-voltage plates (1 m long, 10 cm vertical separation) of the beam separator and were focused through the chopper slit and then onto the μSR sample. The beam slowly converged to a waist located between two 1.5-cm-diam collimators just upstream of the sample; these collimators reduced the beam size at the sample position to somewhat less than that of the sample.

To turn the beam on, the separator E and B fields were adjusted to allow muons to pass through the chopper slit (a 2.9-cm-diam hole in a 3.8-cm-thick lead plate); the beam size at the slit was approximately 2.5 cm FWHM in the vertical direction, which was the direction of beam deflection by the separator. At the same time, electrons were deflected away from the slit, removing them from the beam.

Beam chopping was accomplished by switching off the separator high voltage, allowing the magnetic field of the separator to dump both muons and positrons at the chopper slit position. Detection of a muon by the M counter at the sample position triggers the switching electronics to turn off the high voltage. The high voltage remains off for the selected wait time to allow the decay positron to appear. At the end of the wait time, the high voltage is switched on to admit the next muon. The separator was operated with a voltage difference of 30 kV between the plates, producing a deflecting field of 3 kV/cm. A waiting time of 64 μs was used. Improved equipment now available will reduce the minimum waiting time to 20 μs and will provide voltage differences up to 50 kV.

4. RESULTS

4.1. Continuous-beam (unchopped) mode

A beam profile monitor was used to measure the beam size at both the chopper slit position and at the μSR sample position. Predicted sizes, obtained using the beam transport code TURTLE /3/, are compared with measured sizes in Table 1.

Table 1
Comparison of predicted and measured muon beam size at chopper slit and sample positions. Sizes are in cm FWHM (horizontal size × vertical size).

Position	Predicted Size	Measured Size
Chopper Slit	3.0 × 2.0	3.5 × 2.5
μSR Sample	1.0 × 1.0	1.2 × 1.2

TURTLE calculations of beam size did not include the effect of multiple scattering in vacuum windows and in the profile monitor windows, so the slightly larger experimentally determined beam sizes are not surprising.

During initial beam tuning, the muon rate, as measured with a 1.3-cm-diam, 2.4-mm-thick scintillation counter at the sample position, was 15.8 kHz average when the proton beam current on the muon production target was 850 μA; this is to be compared with a TURTLE prediction of 32 ± 2 kHz. The discrepancy is attributed to the fact that the SMC bending magnet settings were not fine tuned to maximize the muon rate, although they were set to their nominal beam design values. It is estimated that optimization would have given a muon rate ten to thirty percent higher than was observed, in which case the measured value would have agreed quite well with predictions.

4.2. Chopped-beam mode

High-voltage rise and fall times (10-90% level) were 500 ns. This experimental result is shown in Fig. 3, which presents the combined results of three measurements each of the muon rate (as determined by counting M counter pulses in a 10-ns time window) as a function of the delay after the start of a pulse used to trigger the voltage turnon/turnoff.

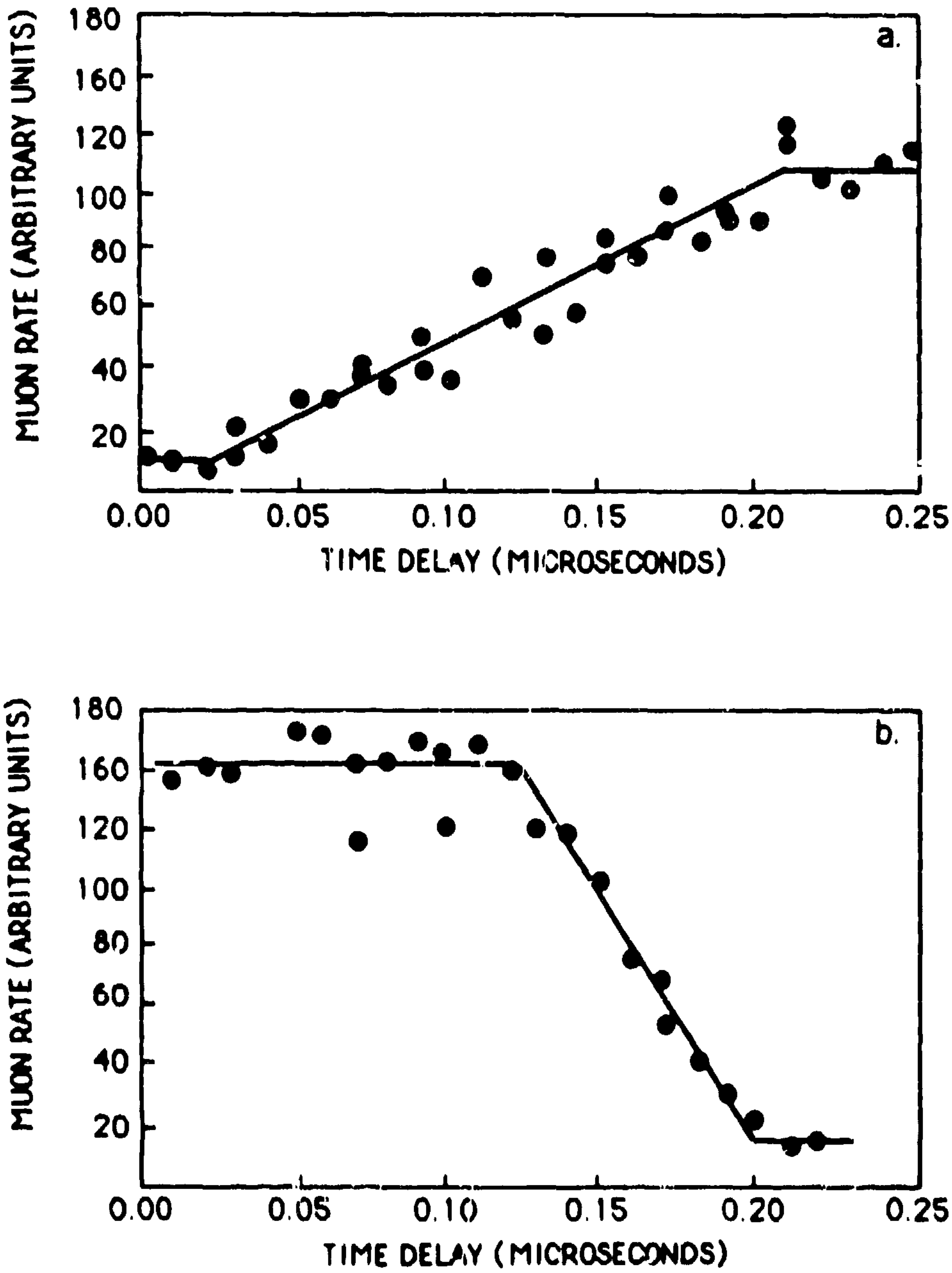

Fig. 3. a. Muon rate vs. time delay after start of pulser signal used to trigger high-voltage turnon. Rise time (10-90%) = 160 ns.
b. Muon rate vs. time delay after start of pulser signal used to trigger high-voltage turnoff. Fall time (90-10%) = 60 ns.

The zero-time reference of the delays is arbitrary; the scale provides a measure from which rise/fall times are tetermined. In the actual M-counter controlled experiments, only 180 ns separated an M-counter pulse and the initial drop in muon rate.

TURTLE simulations, which assumed linear rise and fall of the high voltage, predicted beam-rate rise/fall times of ≈100 ns while the measured values were 160 ns and 60 ns, respectively. The fact that the measured fall time is shorter than predicted is reasonable since, when the high voltage is turned off, the voltage decreases relatively rapidly during the initial part of the exponential-like (not linear as in the TURTLE calculations) voltage falloff. It is during this early, rapid voltage drop that the beam is deflected off the chopper slit. The rise time is somewhat longer because it is during the late, slowly varying part of the voltage rise, when it is almost up to full value, that the beam begins to pass through the slit again.

The probability of muon pileup is minimized by turning the beam off with the chopper, not only as quickly as possible after the arrival of a first muon, but also as completely as possible. The completeness of turnoff is termed the extinction efficiency and is the ratio of muon flux with chopper off to flux with chopper on. The system as tested gave an extension efficiency of 1:1540.

Because scattered beam positrons can give false positron signals in the telescopes, it is important that the chopper/separator remove as many positrons as possible from the beam. The μ/e ratio was found to be ≈20:1 with the separator on.

The experimental asymmetry, a, which appears in the expression

$$N(t) = N(0)\exp(-t/\tau)[1 + aG(t)\cos(\omega t + \phi)]$$

that describes transverse-field data, was typically 0.18–0.22, much the same as observed in decay muon beam experiments with the present geometry.

To detect any unexpected differences between the histograms measured by telescopes in different orientations, three positron telescopes were used, one downstream of the sample, and one each above and below. The histograms from all three telescopes were found to be similar. Only the upper telescope was used to directly observe histogram rates in the chopped-beam mode. The measured rates, as a function of the size of the beam-limiting slit in the SMC, were compared with TURTLE predictions based on the unchopped mode muon rates. Figure 4 shows both measured and predicted histogram rates for the upper telescope as a function of the size of the beam-limiting slit. Error bars on the calculated points reflect a combination of statistical uncertainties in the Monte Carlo TURTLE results and statistical errors in unchopped mode measurements. As expected, a monotonic rise in the rate was seen as the slit size increased, but, since the chopper could not turn the beam off instantly, pileup eventually set in, causing event rejection; the histogram rate increased to a maximum and then decreased with increasing incident muon rate (increasing slit size) just as it does in the unchopped-beam mode. In this case, however, maximum projected data rates were much higher than for unchopped beam experiments because beam chopping does substantially reduce the probability that a second muon will get through to cause pileup.

The maximum measured histogram rate was roughly 200 Hz for the single telescope with a chopper cycle time of 64 μs. With new electronics, now available, that allows cycle times as short as 20–25 μs, the event rate will increase to roughly 500 Hz compared with a maximum rate of about 100 Hz attainable with the unchopped LAMPF decay muon beam. Measured values of the histogram rate were somewhat lower than the calculated values, which were based on the assumption of 100% positron telescope efficiency. Since the positron counters were not 100% efficient, this result is not surprising.

μSR data taken using unchopped decay beams has typically had time-independent backgrounds of 1–3% of the rates in the early-time channels. This background has been attributed to muons that stop in the sample region

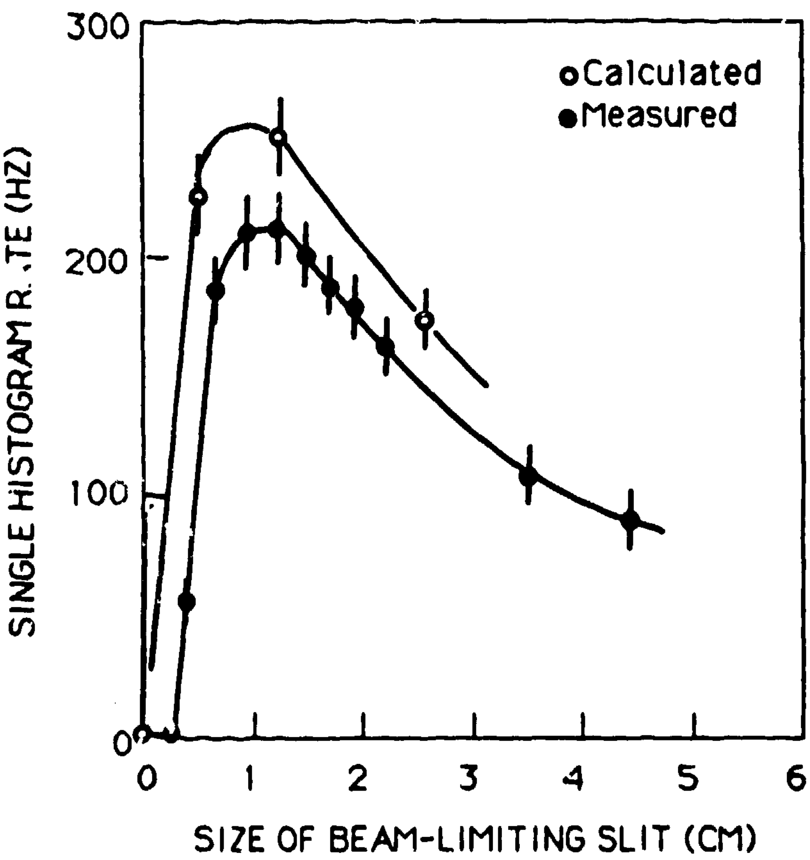

Fig. 4. Comparison of calculated and measured histogram rates for the chopped-beam mode.

signals uncorrelated in time with the muon that initiates a given time interval. It was expected that, by turning the beam off as soon as a muon arrives, the background would be significantly reduced since only one muon could be in the vicinity of the sample at any time. The backgrounds observed in the chopped beam mode were higher than expected, however, being ≈1%, and had a small time-dependent component. Although the backgrounds are still not completely understood, it is assumed that they have the same origin as in the experiments done with unchopped decay muon beams. If this is the case, then one way to reduce the background would be to design more effective muon beam collimation.

5. CONCLUSIONS

It has been demonstrated that use of a beam chopper to avoid muon pileup in time-differential μSR experiments is an exceptionally effective technique for increasing data rates at low-duty-factor-beam facilities such as LAMPF, giving increases as great as a factor of five above those attainable with unchopped beams. Similar rate increases may be attainable at continuous-beam facilities if there is sufficient muon flux available and if the chopper electronics can be designed to tolerate the high power dissipation associated with continuous chopper pulsing. It is probable that, with well-designed collimators, backgrounds significantly less than those obtained in decay beam experiments can be attained.

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